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Beam Dynamics Issues at Fermilab

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I. BOOSTER

A new 400 MeV linac was commissioned in September 1993 as the injector for the Booster. Raising the injection energy from 200 MeV to 400 MeV reduces the self-field space charge by almost a factor of two. However, this reduces the momentum spread and blowup of the normalized transverse emittances (now roughly 6π mm-mrad) as well. As a result, when the intensity is above 2.5×10^{12}, a mode $m = 0$ horizontal head-tail instability develops after crossing transition blowing up the horizontal emittance. The horizontal natural chromaticity is about one unit negative and the present sextupole system is not strong enough to reverse its sign. Studies are being made for additional sextupole installation to cope with the problem.

II. TRANSITION CROSSING OF THE MAIN RING

The Main Ring receives bunches from the Booster at momentum 8.9 GeV/c, passes through transition at $\gamma_t = 18.85$, and finally reaches 150 GeV/c for bunch coalescence or 120 GeV/c for production of antiprotons. There is no special provision for transition crossing. Usually there is a beam loss of $\sim 5\%$ and a longitudinal emittance blowup to ~ 0.2 eV-sec independent of the intensity and emittance at injection, except in the nonoperational situation of very low intensity and very small emittance. The emittance blowup is generally considered to be a result of (1) nonlinearity of the orbit length dependence on momentum, (2) mismatch of bunch lengths due to space charge, and (3) negative-mass instability. The loss occurs mostly at transition and is attributed to scraping due to the small physical aperture of the ring.

In the run that ended in the early part of 1992, the initial bunch emittance was as large as 0.16 eV-sec at 1.6×10^{10} ppb, and nonlinearity was naturally singled out as the culprit in transition crossing. Within the nonadiabatic time interval, the focussing rf force produces very little synchrotron motion. As a result, particles situated at the higher-rf-voltage side continue to gain energy with respect to the synchronous particle, while those particles situated at the lower-rf-voltage side continue to lose energy. This is the reason why the momentum spread becomes larger and larger and the bunch becomes tilted in phase space, leading to eventual scraping. To get rid of this effect, Griffin proposed a *focus-free transition crossing* (FFTC), which with the aid of a third-harmonic cavity flattens out the rf force in the interval of a few msec before and after transition. Such an experiment was performed at the Main Ring during the collider run from April 1992 to May 1993. We did see the bunch lengthen instead of shorten when crossing transition, indicating that the bunch sheared without increasing the momentum spread, and as a result, no beam loss was observed. However, due to the nonlinearity of the path length as a function of momentum, the bunch did not shear back to its original shape after

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the switching of the rf phase at transition. The bunch therefore did not match the subsequent recapturing rf bucket, resulting in quadrupole oscillations and eventual blowup of the emittance due to smearing.

During this run, the coupled-bunch instability in the Booster had been fixed by damping the relevant higher-order modes in the cavities. The bunches received by the Main Ring had a small emittance of 0.06 to 0.07 eV-sec, which was almost independent of bunch intensity. In this regime of small emittance, the dominant effect of transition crossing became negative-mass instability instead. Unfortunately, the FFTC scheme might even enhance this instability because the momentum spread that was required for Landau damping was smaller than that incurred in the ordinary transition crossing scheme. To sum up, the FFTC scheme has been successful in almost eliminating beam loss across transition, but has not been able to eliminate the growth of longitudinal emittance.

In the present run which is starting up right now, the third-harmonic cavity was removed and a new ramping curve is used, which boosts the rate of change of gamma at transition from $\dot{\gamma} \sim 80$ to ~ 120 sec^{-1}. The nonadiabatic time was reduced from 3.0 msec to 2.3 msec. However, we continue to see a beam loss of 3 to 6% across transition. This suggests problems for the future Main Injector which has a design of $\dot{\gamma} \sim 140$ sec^{-1} when crossing transition.

A suggestion for the present Main Ring is to blowup the bunch emittance to roughly 1.2 eV-sec before crossing transition, hoping that the blowup after transition due to negative-mass instability will be smaller. However, this is not an easy task, because there is only about 120 msec before transition, which is not enough to smear a bunch injected deliberately not at the center of the bucket. One possibility is to install a higher-order harmonic cavity and introduce some phase modulation. Another suggestion is to reinstall the third harmonic cavity to eliminate the few percents of beam loss using the FFTC scheme.

III. COUPLED-BUNCH INSTABILITY

From 50 GeV upward, the Main Ring exhibits coupled-bunch instability for 9 to 11 bunches. The offending resonance in the cavity has been measured to be at 225 MHz with a quality factor of $Q \approx 300$. The growth rate of this type of instability depends on the R/Q value of the higher-order cavity mode and not on the shunt impedance R. Thus, passive mode dampers, which reduce R but leave R/Q unchanged, cannot be used to cure this instability. One suggestion is to monitor the position and beam loading of each bunch and feed forward exactly the same voltage into the cavities at exactly the right time. The exact cancellation of the beam loading should be able to suppress the coupled-bunch instability. However, only a tiny fraction of the beam loading is responsible for the coupled-bunch instability. The pickup-feedforward device needs to be extremely accurate. The necessary tolerance of such a device is presently under investigation.

IV. SNAP COALESCENCE

With the usual adiabatic coalescence, the $h = 1113$ 53 MHz rf voltage $V_{rf} = 800$ kV at the 150 GeV flat top is reduced adiabatically and then turned off. A $h = 53$ rf with a $h = 106$ component is turned on to rotate the 11 bunches to be coalesced by 90°. These 11 bunches are then recaptured into one $h = 1113$ rf bucket at $V_{rf} = 800$ kV. This whole adiabatic process takes about 1.2 sec, and the half fractional momentum spread of the bunches dips to a very small value, for example, $\delta \approx 5.7 \times 10^{-5}$ when the initial bunch emittance is 0.2 eV-sec. During this time, the coupled-bunch instability discussed in the last section develops to such an extent that the final capture efficiency becomes very low.

In the snap coalescence scheme, the $h = 1113$ rf voltage is snapped down suddenly from $V_{rf} = 800$ kV to about 50 kV so that the bucket is just tall enough for the bunches. At this V_{rf}, the bunches are allowed to rotate by 90° to swap their larger momentum spread with the smaller phase spread. The $h = 1113$ rf is then turned off and the 11 bunches are then rotated by the $h = 53$ rf for 90° and then recaptured by a $h = 1113$ bucket exactly in the same way as in the adiabatic coalescence. The whole snap coalescence takes only about 150 msec so that the coupled-bunch instability does not get enough time to develop. The capture efficiency is over 70% for 11 bunches with an initial area 0.2 eV-sec. This boosts the luminosity of the Tevatron by a factor of 1.7.

Most of the problem of the snap coalescence comes from the 90° rotation under the $h = 1113$ voltage of 50 kV. Because of the nonlinearity of the sinusoidal rf voltage and the tight bucket for the momentum spread of the bunch, the bunch shapes like a snake rather than an ellipse after the rotation. This results in larger momentum spread than that in the adiabatic coalescence just before the turning on of the $h = 53$ rf, and limits the amount in the final capture into an $h = 1113$ bucket.

A second-harmonic ($h = 2226$) cavity has been installed in the present collider run. This cavity linearizes the rotation rf to a certain extent, and a capture efficiency of over 80% has been achieved.